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Climate change and landscape development in post-closure safety assessment of solid radioactive waste disposal: Results of an initiative of the IAEA

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ABSTRACT

The International Atomic Energy Agency has coordinated an international project addressing climate change and landscape development in post-closure safety assessments of solid radioactive waste disposal. The work has been supported by results of parallel on-going research that has been published in a variety of reports and peer reviewed journal articles. The project is due to be described in detail in a forthcoming IAEA report. Noting the multi-disciplinary nature of post-closure safety assessments, here, an overview of the work is given to provide researchers in the broader fields of radioecology and radiological safety assessment with a review of the work that has been undertaken. It is hoped that such dissemination will support and promote integrated understanding and coherent treatment of climate change and landscape development within an overall assessment process.

The key activities undertaken in the project were: identification of the key processes that drive environmental change (mainly those associated with climate and climate change), and description of how a relevant future may develop on a global scale; development of a methodology for characterising environmental change that is valid on a global scale, showing how modelled global changes in climate can be downscaled to provide information that may be needed for characterising environmental change in site-specific assessments, and illustrating different aspects of the methodology in a number of case studies that show the evolution of site characteristics and the implications for the dose assessment models.

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Overall, the study has shown that quantitative climate and landscape modelling has now developed to the stage that it can be used to define an envelope of climate and landscape change scenarios at specific sites and under specific greenhouse-gas emissions assumptions that is suitable for use in quantitative post-closure performance assessments. These scenarios are not predictions of the future, but are projections based on a well-established understanding of the important processes involved and their impacts on different types of landscape. Such projections support the understanding of, and selection of, plausible ranges of scenarios for use in post-closure safety assessments.

1. Introduction

Environmental change has long been recognised as an issue requiring consideration within post-closure safety assessments (PCSAs) for solid radioactive waste disposal (Lawson and Smith, 1985; BIOCLIM, 2004; SKB, 2006; Posiva, 2006; LLWR, 2011). The International Atomic Energy Agency (IAEA) has played a significant role in coordinating and consolidating research and assessment methods in this context, notably in setting out an overall “Reference Biospheres” methodology for assessing radiation doses following radionuclide releases from radioactive waste repositories (IAEA, 2003). Subsequently, the European Commission project BIOCLIM supported better understanding of how to address climate change within PCSAs (BIOCLIM, 2004) and the IAEA provided a further international locus for analysis of how to address environmental change in PCSA. The study was carried out as part of the second phase of the IAEA programme on Environmental Modelling for RAdiation Safety (EMRAS II), was completed in 2012 and reported in IAEA (2016). That report was prepared by a wide range of participant organizations, including regulators, operators and technical support organizations from many countries. The scope of the work included the following:

- Use of data for present-day conditions at a range of different sites with different climate and other characteristics that might be considered as suitable analogues for future conditions at a specific site;
- Modelling of the important features of the soil-plant system in different climatic and other conditions;
- Use of dynamic system modelling of climate and landscape change to better understand the possible future biosphere conditions at a site, on a site-specific basis;
- A review of international recommendations and national requirements and guidance on how to address environmental change in demonstrating compliance with post-closure protection objectives.

The EMRAS II study (IAEA, 2016) showed that it is widely recognised that environmental change may affect the radiological impact arising from any eventual releases of radionuclides from radioactive waste repositories into the biosphere. This is reflected in international recommendations on post-closure safety (App 4 of IAEA, 2016; IAEA, 2012; ICRP, 2013).

In the EMRAS II study, two main approaches were identified to addressing environmental change. The first, the analogue approach, was based on the use of data for present-day conditions at a range of sites, with different climate and other characteristics, that might be considered as suitable analogues for future conditions at the specific site in question. The other main approach, which has been developed further in the MODARIA project described here, is to model explicitly the dynamic evolution of the biosphere in response to the main environmental change drivers, i.e. climate change and geomorphological changes, notably associated with sea-level changes at coastal sites, but also potentially linked to significant erosion in areas of geological uplift. This approach relies on integration of the modelling of the evolution of climate, hydrology, landform, radionuclide release from the geosphere, radionuclide migration and accumulation, and land-use. Both approaches were demonstrated to be useful in the EMRAS II study and can be considered complementary.

Detailed consideration was also given to the modelling of the soil-plant sub-system in a range of different fixed climate and other conditions. This information can be useful within the dynamic and analogue approaches, depending on the level of temporal resolution adopted. It also provides a useful starting point for assessing transient effects linked to environmental change.

It was recommended in the report of the EMRAS II study (IAEA, 2016) that future work should be directed to providing a consensus approach to addressing climate change as part of a PCSA.

Based on these recommendations, a working group (WG6) was set up within the IAEA's follow-up assessment programme, MODARIA (Modelling and Data for Radiological Impact Assessments), to develop a common framework for addressing climate change in post-closure radiological assessments of solid radioactive waste disposal in both near-surface and deep geological disposal facilities. The authors of this paper comprise the members of the working group that contributed substantially to the studies that were undertaken. The output from the working group, as described in this paper, represents the personal views of the members of the working group and cannot be interpreted as representing the views of the IAEA or its Member States.

Specifically, the overall objective of the working group was to further develop the understanding of how the biosphere may change from the present into the far future in a wide range of regional and local contexts relevant to the near-surface, intermediate depth or deep geological disposal as may be relevant to different types of solid radioactive wastes (IAEA, 2009). Thus, the emphasis was on modelling potential patterns of climate and landscape change to provide a context in which, e.g. appropriate analogue systems could be selected, and soil-plant modelling studies could be performed. To facilitate the work, a classification scheme was established for the different types of disposal facility that have been developed or proposed, so that the implications of the work for these different types of facility could be established. The timescales of relevance and the types of environmental change of most significance differ between these various types of facility.

Although this project was undertaken in the context of safety assessments of the disposal of solid radioactive wastes, the methodology that has been developed and the results that have been obtained are relevant in much wider contexts. Thus, considerations of climate and landscape change are directly relevant to evaluating the radiological impact and assessing the potential for remediation of sites with existing radioactive contamination, e.g. those that have arisen from uranium mining and milling and other legacies (Sneve and Strand, 2016). More generally, the work on modelling the long-term climatic consequences of various carbon dioxide emissions scenarios can be used to inform assessments of the long-term environmental impacts of those scenarios, i.e. beyond the next few centuries, which is the typical time horizon of climate-change impact assessments.

The results of WG6 have been outlined in a brief conference paper (Lindborg et al., 2017). The current paper provides a more detailed technical description of the methodology and illustrative examples of application. The referenced research reports and journal papers should be consulted for a comprehensive account of the science that underpins the presented methodology.

2. MODARIA project activities

The main tasks undertaken to achieve the MODARIA project objective were as follows.

- Defining the key processes that drive environmental change (mainly those associated with climate and climate change), and describing how a relevant future may develop on a global scale. These drivers are quantitative and can be extracted from the existing scientific consensus on global historical climate and landscape evolution. The results can be used to describe the future environments, which are called ‘reference futures’ and ‘future variants’. The terminology was designed to show that they are not predictions, but examples that provide relevant input for addressing specific issues in a safety assessment.
- Developing a methodology (as a conceptual framework) accounting for environmental change that is valid on a global scale, and showing how global changes in climate can be downscaled to provide information that may be needed for site-specific assessments.
- Illustrating different aspects of the methodology in several case studies (for specific sites and regions) that show the evolution of site characteristics and the implications for the dose assessment models, including the justification for abstraction into simplified assessment-level models. This was intended to address: (a) changes in the potentially affected environment prior to any assessed radionuclide release to the biosphere, and (b) changes occurring after or while releases are assessed to occur, including possible transient effects that may be relevant to resulting potential exposures.

The outputs from these various tasks are described in subsequent sections of this paper, but somewhat reordered, so that all the climate-related activities are addressed first, before considering the implications for landscape development.

3. Drivers and controls on long-term climate change

On timescales of a few hundred to one million years or longer, which are relevant to different types of disposal facility (see appendix IV of IAEA, 2016), the principal controls on climate are greenhouse-gas and aerosol concentrations in the atmosphere, and variations in the orbital characteristics of the Earth. Other controls, internal to the climate system, include variations in ice-sheet extent and changes in ocean circulation. These internal controls are represented in various types of climate model, whereas the external controls are treated as time-varying boundary conditions imposed on those models. The orbital characteristics and associated varying patterns of insolation can be accurately calculated from many million years in the past to many million years into the future using the methods of celestial mechanics (Laskar et al., 2004, 2011). The time variations in atmospheric greenhouse-gas and aerosol concentrations are more difficult to assess than these orbital variations, because they involve both human and natural contributions, with non-linear feedbacks existing between the processes controlling these concentrations and climate (Lord et al., 2015, 2016). However, because most greenhouse gases and aerosols have residence times in the atmosphere ranging from months to a few centuries (IPCC, 2013), attention can be focused on carbon dioxide, which is identified as the main greenhouse gas (IPCC, 2013) and exhibits significant components of residence in the atmosphere ranging up to more than 100 kyr (Lord et al., 2015, 2016).

In the context of the MODARIA project, using the Earth system Model of Intermediate Complexity (EMIC) cGENIE, the time evolution of atmospheric concentrations of carbon dioxide was studied for scenarios in which various amounts and patterns of fossil fuel emissions were simulated (Lord et al., 2015, 2016). In the first set of simulations, pulse releases of 1000 to 20,000 PgC (1 PgC = 1 10^{15} gC = 1 GtC) were simulated. For comparison, emissions due to human activities since the beginning of the industrial revolution have been about 300 PgC and fossil fuel reserves that are currently potentially technically and economically viable are about 1000 PgC. In addition, there are a further 4000 PgC of identified fossil fuel reserves for which economic extraction may be possible in the future, and about 20,000 to 25,000 PgC of non-conventional resources, such as methane clathrates, that could potentially be exploited in the future (Lord et al., 2016).

Based on the results of this first series of cGENIE simulations, a generalised multi-exponential response function for pulse releases of any magnitude was developed. In this generalised response function, the coefficients of the exponential components were defined as polynomial functions of the total magnitude of the pulse release.

A second set of simulations comprised a set of time-dependent releases in which the time dependence was characterised as having a logistic form. Results from these experiments were compared with a convolution approach based on the pulse-emission results for the same total emissions. It was found that the convolution approach gave a very close representation of the time-dependent release calculations. After the first 200 years of the emissions period, differences between the two approaches were never more than a few percent of the total atmospheric carbon dioxide concentration. Thus, the convolution approach was found to be sufficiently accurate to be recommended for relating time-dependent emissions scenarios to atmospheric carbon dioxide concentrations in all solid radioactive waste disposal contexts for which such scenarios are required over a range of timescales from the next few hundred years out to one million years after present (AP). However, as with any comparable model, the cGENIE model has a range of internal model parameters that are poorly constrained. As such, the analysis could be repeated with a range of different internal model parameters to quantify the uncertainty in the model results. Furthermore, as only one EMIC was used, confidence in the robustness of the approach would be improved by repeating the analysis with other EMICs that also include representations of the global carbon cycle.

4. Modelling of global climate change

Although cGENIE provides projections of climate as well as of atmospheric carbon dioxide concentrations, it does not currently include orbital variations or changes in ice sheets. Also, more detailed projections may be required as input to the performance assessments. In principle, projections of future climate evolution can be obtained using models of varying complexity ranging from high-resolution Earth System Models (ESMs) through Atmosphere-Ocean General Circulation Models (AOGCMs), Earth system Models of Intermediate Complexity (EMICs) to Simple Climate Models (SCMs). In general terms, the range from ESMs to SCMs involves decreasing complexity of the model physics and dynamics of the different components of the climate system as compared with the real world, as well as decreasing spatial and temporal model resolution. The computational cost of state-of-the-art ESMs and AOGCMs prevents use of these models for modelling of more than a few centuries to millennia. However, in the MODARIA project, an innovative approach was developed that permitted an ensemble of AOGCM calculations to be used in combination to simulate climate change in non-glacial conditions on a quasi-continuous basis over future periods of up to one million years. That approach, described as use of a climate emulator, is outlined below. Full technical details are given in Lord et al. (2017).

The principle underlying the climate emulator is to first compute an ensemble of AOGCM results for a range of boundary conditions (in this case orbital characteristics and atmospheric carbon dioxide concentrations, and two ice-sheet configurations) that spans the domain of interest. Results for any other set of boundary conditions within that domain can then be obtained by interpolation between the results for various members of the ensemble using an appropriate weighting procedure. Optimization of the interpolation procedure is complex, because the quantities being interpolated comprise many climatological variables (e.g. mean monthly temperature and precipitation) defined on a three-dimensional spatial grid.

The emulator used was based on techniques developed previously by the Catholic University of Louvain (Araya-Melo et al., 2015) and was calibrated (i.e. the weighting factors used in interpolation were optimised) using mean annual 1.5 m surface air temperature (SAT) data produced using a Hadley Centre AOGCM (HADCM3M2.1E, Valdes et al., 2017) for an ensemble of model experiments with ice-sheet configurations characteristic of Quaternary interglacial episodes.

HADCM3M2.1E has been extensively used in shorter-term climate modelling inter-comparisons and has a sensitivity to atmospheric carbon dioxide concentrations that is intermediate between the least and most sensitive models included in those inter-comparisons. Although the emulator was trained on SAT in this application, it could be trained on other spatially distributed variables available from the AOGCM, or on multiple sets of such variables, e.g. both temperature and precipitation datasets. Note that although trained on a single dataset (in this case SAT), the emulator can then be used to interpolate any dataset provided by the AOGCM, but the interpolation is based on a weighting scheme optimised to the variable or variables used in the training.

Nucleation and development of the Laurentide and Fennoscandian ice sheets, and expansion of the Greenland ice sheet to greater than its present-day extent, were not addressed in this study, but loss of the Greenland ice sheet under warm-world conditions was studied in a separate ensemble of runs. An ongoing study, being sponsored by SKB and Posiva, has developed an approach that will allow the emulator to be used for conditions both warmer and colder than the present day, extending to full glacial conditions comparable with those that occurred at the Last Glacial Maximum (Marine Isotope Stage 2). The emulator was then used to project mean annual SAT and precipitation at 1 kyr intervals for the next 1 Myr to cover a wide range of scenarios that do not involve initiation of the next period of Northern Hemisphere glaciation. The current interglacial is projected to be much longer than previous Late-Quaternary interglacials because of greenhouse-gas warming and a low variation in insolation. A variety of studies are ongoing worldwide to estimate the potential duration of this projected episode (see also Section 5). These studies indicate that the current interglacial may persist for a period of between about ten thousand years up to more than one hundred thousand years. However, on timescales of more than a few hundred thousand years, glacial-interglacial cycling is expected to recommence, so the results from the current emulator on longer timescales are of limited relevance, hence the ongoing work to extend the scope of the emulator to conditions both colder and warmer than those at the present day. In this paper, results from the emulator are shown to 200 kyr After Present (AP), as this is considered a reasonable estimate of the likely duration of the current interglacial under a business-as-usual carbon emissions scenario (see also Section 5). For near-surface disposal, an assessment timescale of about ten thousand years will often be appropriate, whereas for deep geological disposal the relevant assessment timescale may be up to about one million years, depending upon the type of waste disposed.

Four CO_2 scenarios were modelled in the ensemble of AOGCM simulations. These adopted logistic CO_2 emissions of 500, 1000, 2000 and 5000 PgC released over the first few hundred years, followed by a gradual reduction of atmospheric CO_2 concentrations by the long-term carbon cycle based on the cGENIE simulations. These four scenarios covered the range of emissions that might occur given currently economic and potentially economic fossil fuel reserves, but not including other potentially exploitable reserves, such as clathrates. Five European locations were selected to illustrate the results obtained. These locations are shown in Fig. 1. Projections of mean annual Surface Atmospheric Temperature (SAT) for these locations are shown in Fig. 2 through to 200 kyr after present. Corresponding projections for mean annual precipitation rate are shown in Fig. 3.

Up until ~20 kyr AP, the behaviour of the climate is primarily driven by the high levels of CO_2 in the atmosphere caused by fossil-fuel emissions and other human activities. However, after this time, changes in orbital conditions begin to exert a relatively greater influence on climate, as the periodic fluctuations in SAT at all locations appear to be paced by the orbital cycles (Lord et al., 2017), which are shown in Figs. 2 and 3.

Within the first 20 kyr period, the largest changes occur during the first few thousand years. The climate-change modelling undertaken for the MODARIA project was primarily directed to multi-millennial timescales. If there was a need for detailed climate projections over the next few thousand years, as might be required for assessments of some near-surface facilities, it might be appropriate to employ one or more AOGCMs in transient mode, driven by time-dependent boundary conditions, to provide more detailed simulations of climate change than can be obtained by use of the equilibrium AOGCM calculations that underpin the emulator.

The influence of declining CO_2 is still evident after 20 kyr, particularly for the higher emissions scenarios, in the slightly negative gradient of the general evolution of SAT. This is due to the long atmospheric lifetime of fossil-fuel emissions (Lord et al., 2016), and is also demonstrated in other studies (Archer and Ganopolski, 2005; Archer et al., 2009; Paillard, 2006).

5. Length of the current interglacial

The results from the climate modelling can also be used, among other things, to throw light on the projected duration of the current interglacial episode. This was of interest because various studies reported in the literature have provided estimates of the remaining duration of the current interglacial period. Brandefelt et al. (2013) reported on seven studies of Earth's climate evolution in the coming 100–200 kyr, performed with five different EMICs and one SCM. In all the EMIC studies, the models were forced by the known future variations in orbital parameters and different scenarios for future atmospheric CO_2 concentrations. At pre-industrial carbon dioxide concentrations, these studies indicate that the present interglacial would be likely to terminate in the very near future, whereas any significant increase in atmospheric carbon dioxide concentrations pushes the end of the interglacial out to either around 50 kyr AP or to more than 100 kyr AP. These results agree with a more recent study by Ganopolski et al. (2016).

However, it is important to recognise that the results of these models may be sensitive to small disturbances and variations of model parameters, as noted by Archer and Ganopolski (2005). The sensitivity of the results to model parameters has been studied by Charbit et al. (2013). They found large differences in the simulated ice-sheet evolution depending on the chosen parameterisation. Furthermore, Crucifix

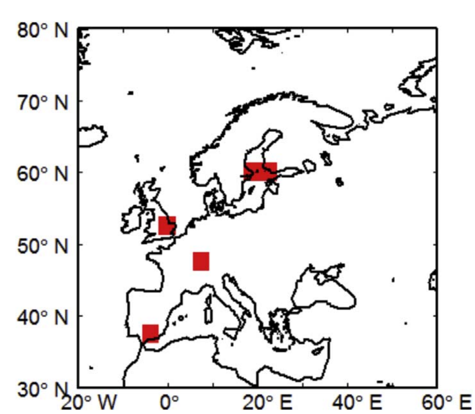

Fig. 1. Map of Europe highlighting the grid boxes that represent the five case study sites. From north to south: Sweden and Finland (left and right box), Central England, Switzerland and Spain. Modified after Lord et al. (2017).

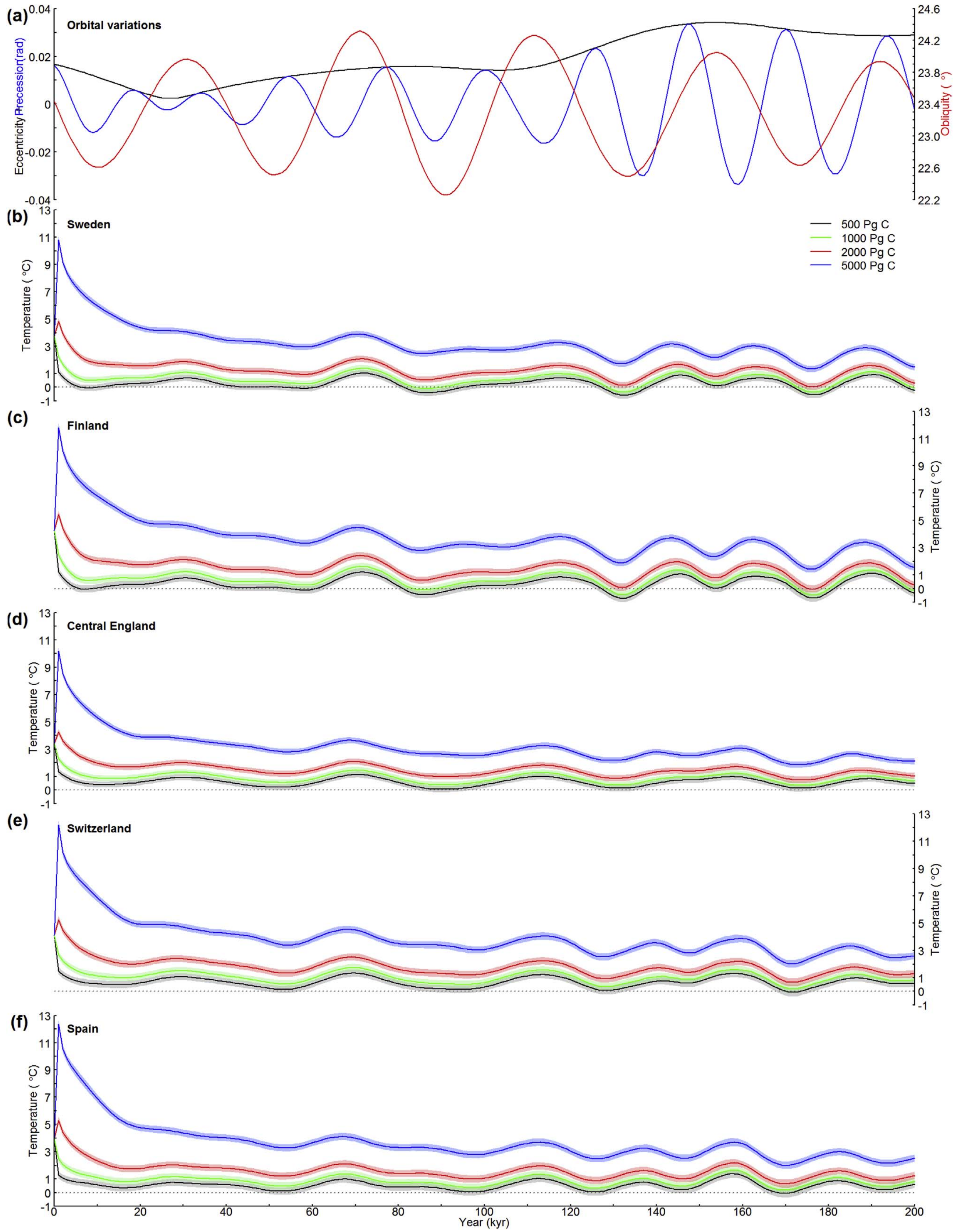

Fig. 2. Emulation of SAT for non-glacial conditions over the next 200 kyr. (a) Time series of orbital variations (Laskar et al., 2004), showing eccentricity (black) and precession (radians; blue) on the left axis, and obliquity (degrees; red) on the right axis. (b) to (e): Time series of emulated grid box mean annual SAT (ºC), modelled every 1 ka, for four CO_2 emissions scenarios; 500 PgC (black), 1000 PgC (green), 2000 PgC (red) and 5000 PgC (blue). Error bands represent the emulated grid box posterior variance (1 standard deviation). SAT is shown as an anomaly compared with the pre-industrial control simulation. Modified after Lord et al. (2017).

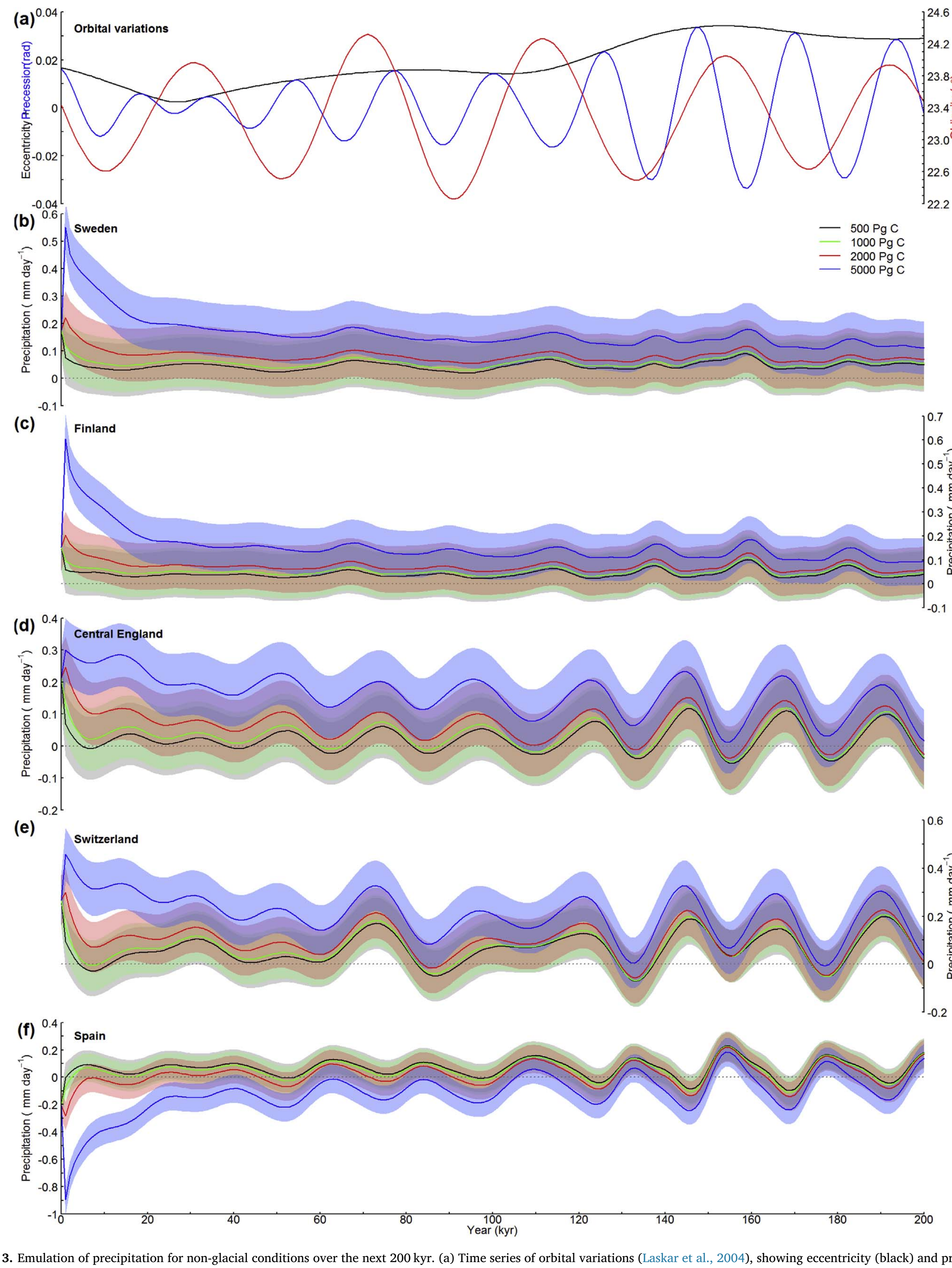

Fig. 3. Emulation of precipitation for non-glacial conditions over the next 200 kyr. (a) Time series of orbital variations (Laskar et al., 2004), showing eccentricity (black) and precession (radians; blue) on the left axis, and obliquity (degrees; red) on the right), modelled every 1 kyr; (b) to (e) Time series of emulated grid box mean annual precipitation (mm^{-1} day) for four CO_2 emissions scenarios; 500 PgC (black), 1000 PgC (green), 2000 PgC (red) and 5000 PgC (blue). Error bands represent the emulated grid box posterior variance (1 standard deviation). Precipitation is shown as an anomaly compared with the pre-industrial control simulation. Note the different vertical axis scales for each site. Modified after Lord et al. (2017).

(2011) showed that the timing of the next glacial inception, simulated with conceptual models designed to capture the gross dynamics of the climate system, is sensitive to small disturbances. He concluded, in agreement with Raymo and Hubers (2008), that the target of developing a dynamical system to convincingly model glacial cycles 'is still elusive'.

In view of these considerations, an empirical model was developed to estimate the likely length of this interglacial (Thorne and Towler, 2017). The basis of this model is an analysis of time-variations in carbon dioxide concentrations in gas inclusions in the Vostok ice core (Petit et al., 1999). The analysis shows that past variations in atmospheric carbon dioxide concentrations over the last 420 kyr can be fully explained by variations in the eccentricity of the Earth's orbit, together with time-correlated stochastic variations with a characteristic sub-orbital timescale of up to 10 kyr (for mathematical details see Thorne and Towler, 2017). Combining this model with the multi-exponential model of carbon dioxide concentration variations due to various emissions scenarios, as described in Section 3, allowed multiple realisations to be made of future variations in atmospheric carbon dioxide concentrations taking variability at sub-orbital timescales into account.

The model described above was used to estimate the remaining duration of the present interglacial. Four different criteria for termination of the interglacial were used. These are somewhat arbitrary, but are based on the observed CO_2 concentrations in the Vostok record. The model predicts that, if there had been no anthropogenic emissions of carbon, the current interglacial would have been likely to end within the next few thousand years, but that there would have been a possibility of it persisting for some tens of thousands of years. However, with 500 PgC of emissions, persistence of the current interglacial for more than ten thousand years is very likely, but it is unlikely to persist for more than 80 kyr. With 1000 PgC of emissions, persistence of the current interglacial for more than 10 kyr is virtually certain to occur and it could persist for up to 120 kyr. With 2000 PgC emitted, there is a small possibility that the current interglacial could end at around 23 kyr or 60 kyr AP, but it is more likely to continue for about 100 kyr and it could continue for around 200 kyr. Finally, with 5000 PgC emitted, the current interglacial is almost certain to continue for 200 kyr or more. Thus, for business-as-usual scenarios, in which fossil-fuel reserves continue to be used, even if the period of use is extended, protraction of the present interglacial beyond 100 kyr AP seems likely to occur. This follows because the primary control on long-term concentrations of carbon dioxide in the atmosphere is the amount of fossil-fuel reserves used, not the period of use (Thorne and Towler, 2017; Lord et al., 2016). Further studies on the potential length of the current interglacial are being undertaken as part of the SKB- and Posiva-sponsored project mentioned in Section 4.

6. Down scaling as relevant to PCSA

Global climate models, as used in support of PCSA, typically provide results at a grid scale of more than 100 km by 100 km, see for example, Fig. 1. This scale is rather coarse for application to local areas or specific sites in post-closure performance assessments, so consideration has been given as to how such results can be downscaled to a finer resolution.

Broadly speaking, three approaches to downscaling exist (Thorne et al., 2016). In rule-based downscaling, selected results from a coarse, long-term climate model (typically an EMIC) are used to define rules by which future conditions at a site are classified into one of a small number of climate classes that can be characterised in terms of present-

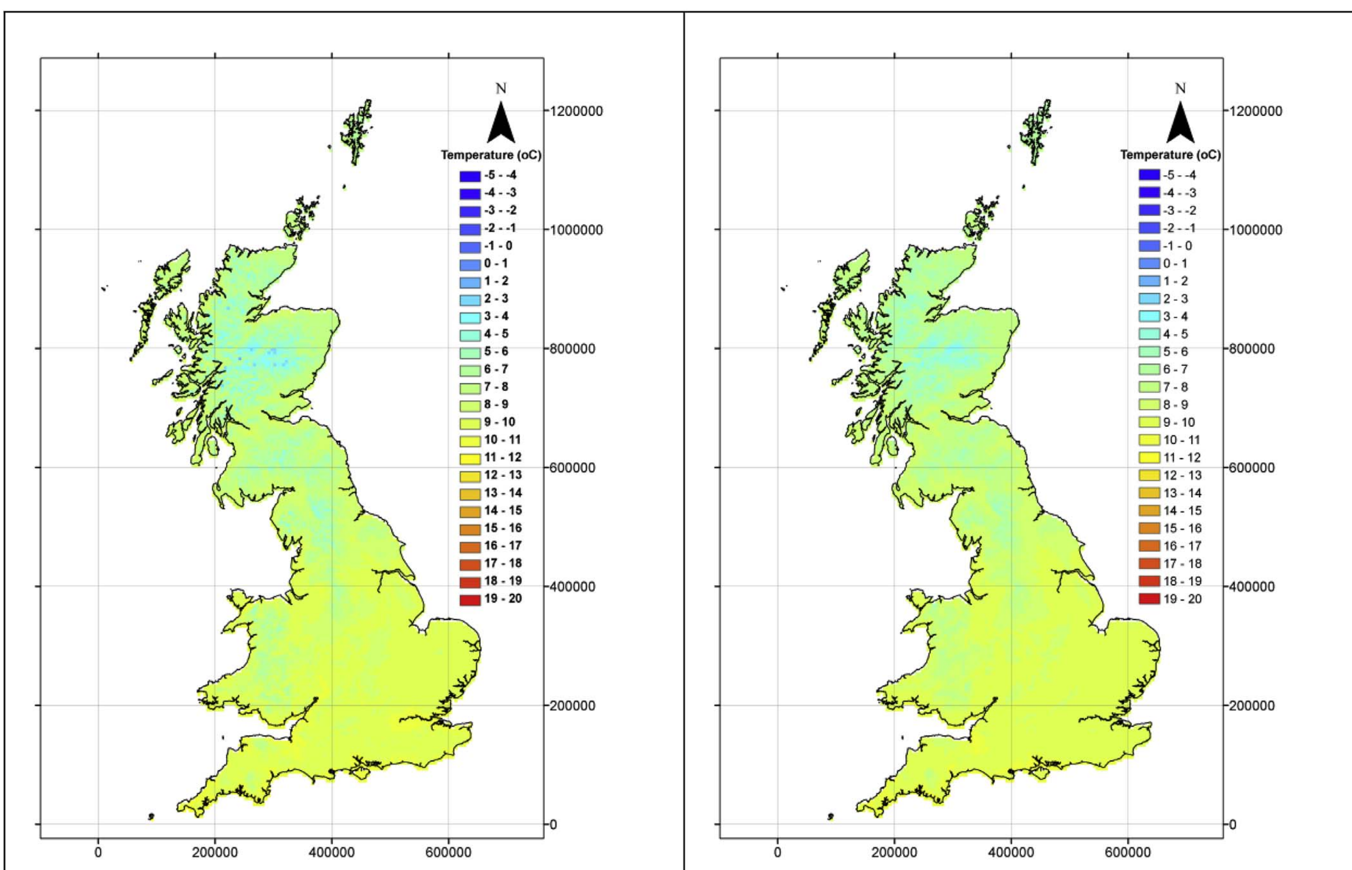

Fig. 4. Observed (left) and predicted (right) mean annual temperature for Britain using a regression applied to the 1961–1990 gridded 5 km by 5 km climatology provided by the Meteorological Office (Thorne et al., 2016).

day instrumental data from various meteorological stations. The rules are generally based on palaeoenvironmental reconstructions of the climate at the site, so the approach is not readily adapted to warm-world situations, such as the current interglacial, for which there are likely to be only less relevant palaeoenvironmental data available.

In dynamical, or model-based, downscaling, a regional climate model is embedded within a global model and takes its boundary conditions from the global model. This technique is not readily applied when global climate characteristics are interpolated between those obtained from various runs of a global climate model using an emulator, as was done in the MODARIA project.

Thus, having eliminated rule-based and dynamical downscaling, the method chosen in this project was physical-statistical downscaling. In this approach, instrumental records are interpreted using a statistical regression technique informed by an understanding of the factors that affect local climate. In the MODARIA project, the usefulness of this approach was investigated by applying it to the UK, as detailed gridded climatological and topographic data for this region were readily available. However, the techniques developed could be readily applied to any other region for which comparable gridded data are available.

In applying physical-statistical downscaling to the UK, a multiple linear regression approach was found to be suitable (Thorne et al., 2016). For mean monthly temperature, the relevant variables in the regression are latitude, longitude and altitude. For precipitation, latitude and longitude are again relevant variables, but altitude is better replaced by an alternative, altitude-related variable that more adequately reflects non-local, for example rain shadow, effects.

For temperature, the simple regression-based approach gave a very accurate representation of the spatial temperature field over the UK, as illustrated in Fig. 4.

For precipitation, the best-fitting regression replaced altitude at each location by the maximum altitude to the west of the specified grid location. This allowed for rain-shadow effects, with Atlantic storms moderated by high ground to the west of the location of interest. The fit is less good than for temperature but was considered fit for purpose for a large part of the area of greatest interest for hosting a geological disposal facility (Thorne et al., 2016).

Further investigations into preferred regression relationships for precipitation are under consideration (Thorne and Walke, 2017). Specifically, thought is being given as to whether it would be better to develop regressions against the original meteorological station data rather than against the gridded data, since artefacts may have been introduced into the gridded data through the interpolation approach adopted. This is less of an issue for temperature than precipitation because the degree of variation of the temperature field within a grid square is less. Although these investigations are specific to the UK, the lessons learned, e.g. in respect to the advantages and disadvantages of using station data compared with gridded data, are likely to be more widely applicable.

7. Implications for landscape evolution and representation in PCSA

In any PCSA, understanding of the site constitutes the basis and scientific support for assumptions on future site characteristics (Lindborg, 2008, 2010; IAEA, 2016). The typical long-term nature of the assessment questions demands support in conceptual understanding of landscape evolution at the specific site (Kautsky et al., 2013). Site properties and ongoing processes tell a story of past climate characteristics and the impact that they have had on the landscape (Anderson and Anderson, 2010; Bradley, 2014). Site information together with an understanding of climate-related processes have been shown useful in describing and modelling the landscape evolution for any given future climate scenario (Lindborg et al., 2013; Becker et al., 2014; Pohjola et al., 2014). However, the output from such modelling work should never be used as predictions. They are physically constrained examples of how a site could react to a given set of climate-related processes (Näslund et al., 2013). This implies that the climate scenario chosen to inform the landscape evolution models, will strongly determine the results. Furthermore, depending on the assessment question, it may be appropriate to test several unlikely as well as likely climate scenarios as drivers of landscape evolution (Lindborg, 2010). A common practice in climate modelling studies is to use a set of models to handle both conceptual and parametric uncertainty relating to the system being simulated. The same strategy can be used when modelling landscape evolution. Different AOGCM-based or downscaled site-specific climate narratives can be applied to explore the range of possible future landscapes given by alternative sets of climate-related processes derived from these narratives and alternative representations of those processes (Lindborg, 2010).

Several local factors play a role in landscape evolution apart from long-term climate-related processes. Properties like latitude, height above sea level, type of bedrock, inland or coastal location, topography, and soil thickness and soil type are, among others, important when understanding landscape responses to external forces (e.g. Selby, 1985; Anderson and Anderson, 2010). Given the site-specific nature of the above factors, the method used to model landscape evolution will be constrained or determined by site-specific features and processes. Below follows a brief discussion on the role of the site context when conceptualising, constructing and site-adapting a landscape evolution narrative.

At coastal locations, several considerations arise (Fish et al., 2010; Lindborg, 2010). Shoreline displacement, caused by eustatic sea-level changes and vertical isostatic crustal movement, play a large role in long-term changes of the landscape. The contribution from isostacy is especially important in previously glaciated regions, where post glacial uplift may still be active. For coseismic movements of the Japanese coastline see Matsu'ura (2015); Ota and Yamaguchi (2004); and Yoshikawa (1985). For aseismic adjustments due to isostatic recovery around the UK, see Shennan et al. (2006). Also, other coastal processes, such as cliff erosion and inundation (Walkden and Hall, 2011), may lead to degradation of a near-surface facility located close to the coast (Fish et al., 2010). Depending on local geology and topography, particularly the shape of the shore profile, a coastal site may be affected in different ways. A low elevation, gently sloping topography will show a faster rate of change compared with a coastline with high or erosion-resistant cliffs, particularly if those cliffs are protected by coarse back-beach deposits (Fish et al., 2010). The importance of elevation and bathymetry maps when calculating effects of shoreline displacement is well illustrated in Brydsten et al. (2009), Lindborg et al. (2013) and Pohjola et al. (2014). For coastal areas that have been previously submerged, a present-day succession can often be seen in a gradient going inland from the shoreline. This site-specific information can be regarded as a present-day analogue for future periods with similar processes acting on the site (Lindborg et al., 2013). For example, in a location with isostatic uplift and shoreline retreat, present-day inland areas can be regarded as analogues for current offshore areas that will emerge from the sea in the future. This type of analogue, if present, is not only evidence of past conditions and process rates, but also a useful tool when calibrating the future landscape narratives.

Inland areas with no past record of having been submerged or at altitudes above the long-term fluctuations of the sea-level will have a different general evolution compared with coastal sites. Erosion and fluvial processes will dominate and cause changes in drainage patterns and soil-layer properties as well as down-cutting into soils and bedrock changing the topography. If the area is situated in high latitudes (or altitudes) the colder periods within each glacial cycle will not only change the temperature, but also trigger features like permafrost, taliks, glaciers (or ice sheets) and cryoturbation processes (Washburn, 1979; French, 2007; Busby et al., 2014).

At inland locations where there are significant variations in topography, fluvial erosion and the incision of river valleys may be the dominant process (Thorne and Kane, 2006; Whipple and Tucker, 1999; Lane et al., 2008). Where Quaternary glacial episodes have resulted in the deposition of a thick layer of unconsolidated sediment, that incision may be into a relatively smooth palaeosurface, permitting estimates to be made of the rate of geomorphological work performed over the period since that glacial episode (Clayton, 1994; Rose, 2010; Thorne and Towler, 2017). Glacial episodes can also lead to the diversion of major rivers, with associated reorganisation of large-scale drainage patterns (in the UK, this has been studied in detail in relation to the River Thames, as discussed in Bridgland, 1994; Clayton, 1994; Rose et al., 1999; White et al., 2010 and Westaway et al., 2015). In France, Andra has selected a site for an underground repository located in Bure, in the southern part of the Meuse district on the border of the Haute-Marne district. At that site, the landform comprises valleys that are deeply incised into a palaeosurface. Although the palaeosurface is ancient, much of the valley incision has occurred during the Quaternary and the maximum depth of incision of around 200 m implies an incision rate of around 100 m per million years. To a large extent, this incision can be attributed to adaptation of rivers to a base level that was typically about 80 m below present-day sea level throughout much of the Quaternary and it has led to substantial reorganisation of the drainage network (Plan General du Referentiel de Site, 2009; BIOPROTA, 2014).

Special considerations arise in arid landscapes, or landscapes that become arid through desertification, where aeolian processes can become important, and fluvial erosion can be dominated by extreme flood events impacting on sparsely vegetated soils. This is an important consideration for Central Spain and was addressed in BIOCLIM (2004). The mean annual temperature of Central Spain at the present day is around 17 °C and it was around 18 °C during the Holocene thermal optimum. However, under the moderate greenhouse-warming scenario adopted in BIOCLIM, the mean annual temperature was projected to rise over the next few hundred years to 32–33 °C. This was projected to be followed by a slow cooling trend to about 28 °C after 5 kyr, about 23 °C after 40 kyr and about 21 °C after 90 kyr. During the initial warming, annual mean precipitation was projected to decrease leading to a markedly arid environment. Based on this evaluation, it was concluded, in BIOCLIM (2004), that it seems highly likely that stream and river flows would decrease, with some smaller streams becoming ephemeral. Due to the aridity, soils would be expected to lose their cohesion and aeolian weathering rates would increase. In some regions, vegetation might be mostly or entirely absent. There would likely be depletion of groundwater sources and reservoir construction for surface-water storage might occur. The soil-moisture deficit could be more than 1 m and there would be a greatly increased irrigation demand where agriculture or grasslands were maintained. Human community characteristics would be driven by the limited water availability, with communities being concentrated near sites of exploitation of deep groundwater resources and close to reservoirs on the main rivers. The availability of detailed climatological projections for warm-world conditions available from the emulator developed in the MODARIA project

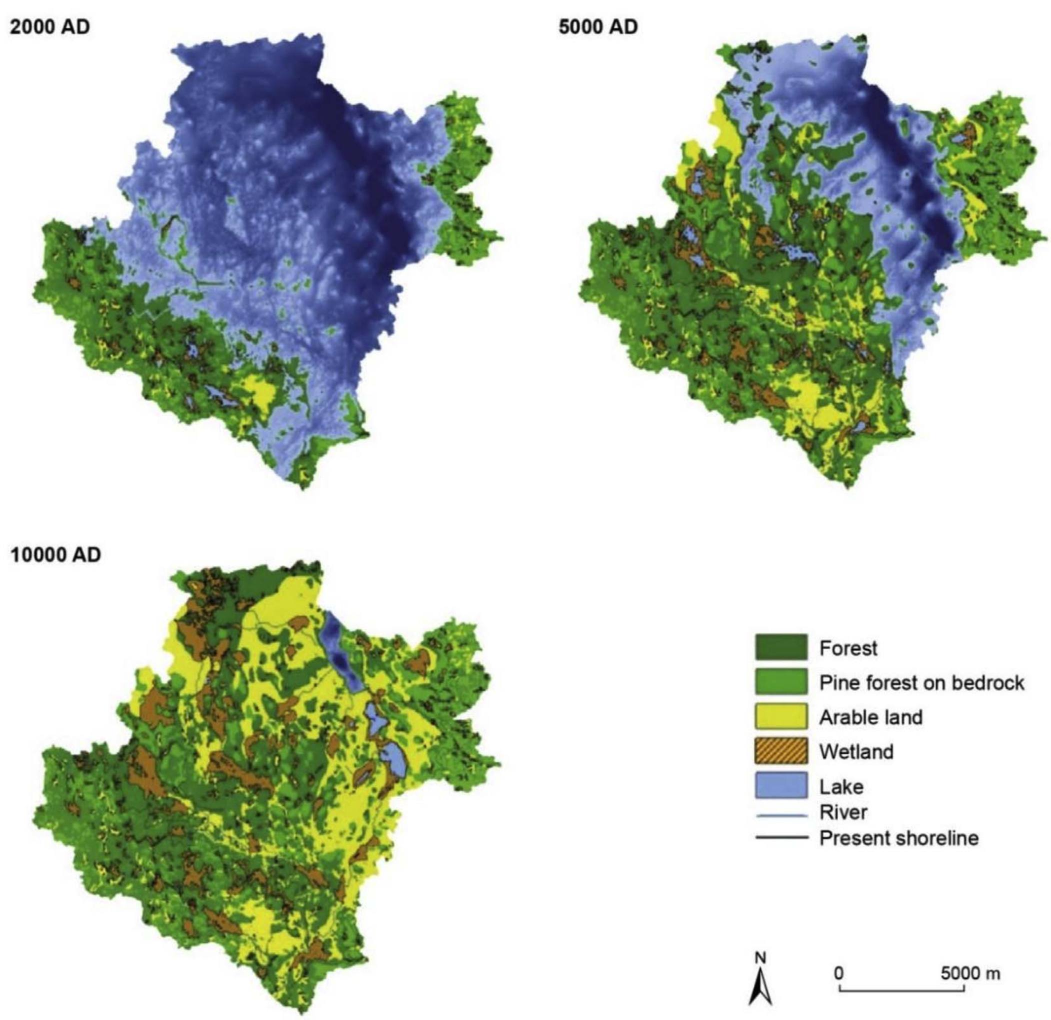

Fig. 5. Distribution of ecosystems at Forsmark at 2000 AD, 5000 AD and 10,000 AD according to the landscape development model presented in Lindborg et al. (2013) and further discussed in Lindborg (2017). The distribution of arable land illustrates the assumption of present-day use of soil types for agricultural areas into the future.

will allow a more comprehensive analysis of climate-change effects on arid landscapes than was possible in BIOCLIM. For example, mean monthly estimates of precipitation minus actual evapotranspiration, and of soil-moisture deficit can be provided to inform assessments of likely changes in vegetation and in the effectiveness of erosion processes.

From the short discussion above it can be concluded that local and site-specific landscape evolutions will be determined by two sets of features; the future climate and the site properties (including location). Therefore, the suggested general method is to start with a conceptual model of the site and then explore what properties and processes will have relevance in landscape evolution for this site. Given that different climate narratives may emphasise alternative sets of climate-related processes, the concept should be tested on all relevant climate scenarios. When the properties and processes are identified, the task of describing the effects on the landscape due to changes in process rates or implications of new processes begins. In Lindborg (2017) the long-term landscape evolution is discussed in general terms and with the Forsmark site used as an illustration (Fig. 5), but, in addition, an in-depth discussion is provided on using climate-related processes to drive a site-specific landscape development model.

The landscape model may be a useful tool in many ways. It can show the effect on a site for different climate scenarios, strengthen conceptual site understanding and support the identification of features, events and processes that are potentially relevant to changes in the surface environment. It can also be used to generate time-dependent data on properties and geometries, and provide information on future site characteristics that can inform discipline-specific modelling, such as that relating to chemistry, hydrology, permafrost and elemental transport, and help to identify, delineate and describe areas to be considered in dose modelling. A landscape model therefore helps to define the site from a dose modelling point of view.

One example of work that uses the landscape development model illustrated in Fig. 5 can be found in Avila et al. (2013). The authors describe the methods used to justify a site-specific dose model using site understanding and how they support the model with time-dependent data derived from the landscape development model. In Fig. 6, an example of a dose calculation is shown that was part of an exercise in a safety assessment for a deep geological repository for spent-fuel disposal at the Forsmark site in Sweden (SKB, 2011).

The implications on dose due to landscape evolution can easily be seen in Fig. 6. During the first period, up to about 4000 years AP, the discharge area is submerged under the sea and is relatively inactive. As the area slowly rises above sea level and transforms into terrestrial and limnic ecosystems, the effective dose rate rises due to changes in transport process rates. Resuspension of sediment during this period due to local topographical features can be seen as small spikes in the effective dose rate curve. The terrestrial stages are then dominated by climate alternations going between temperate and periglacial climate conditions. The two climate scenarios illustrated have different implications for land use and the possibility to use groundwater resources, e.g. it is assumed that no well water is extracted and used during permafrost conditions. This, in turn, is manifested in different effective dose rates.

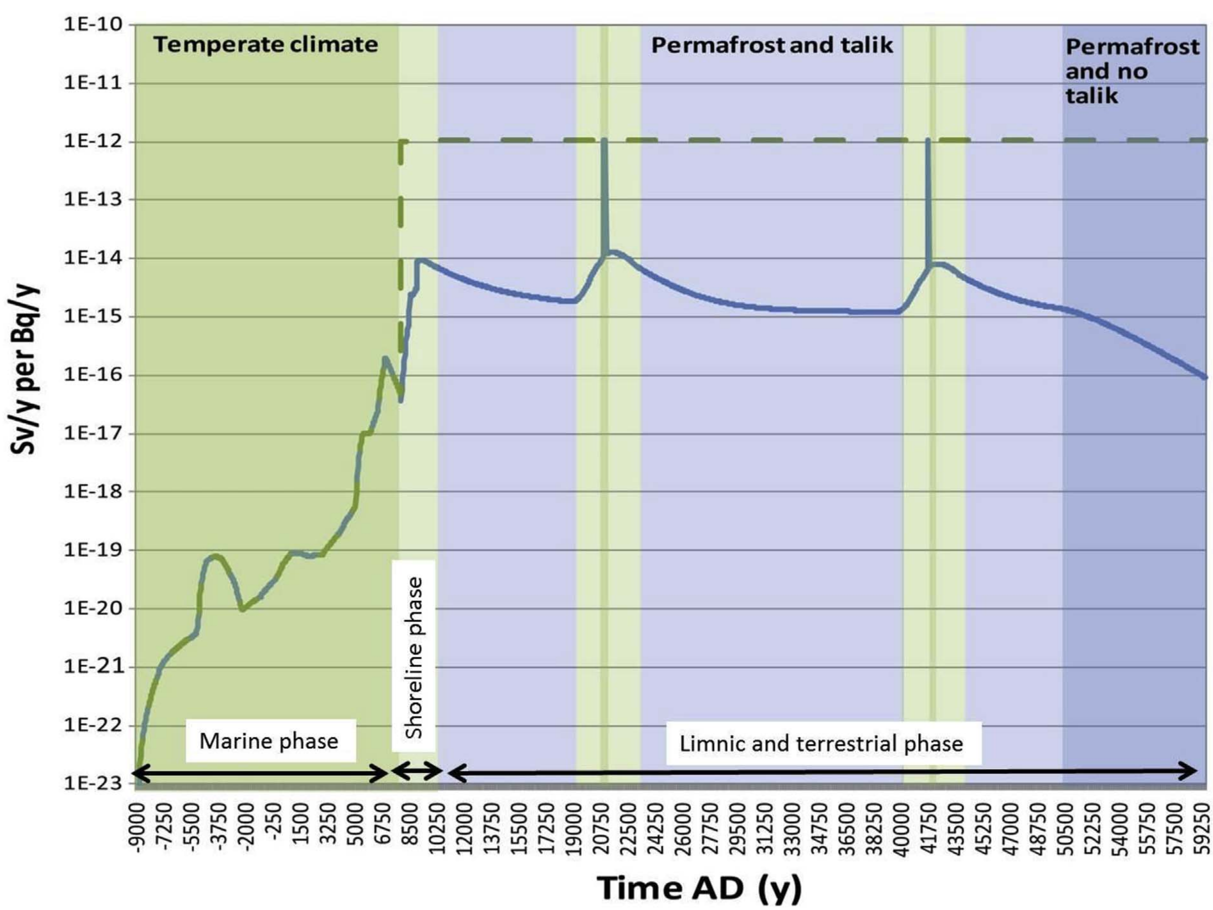

Fig. 6. Example of effective dose rate for unit release rate of Ra-226 from time-dependent simulations of a discharge area at Forsmark, Sweden. Landscape development data from a climate variant assuming that the current interglacial, with temperate climate conditions (green background) is followed by a period of periglacial conditions (blue background) with permafrost features and processes. Major landscape development phases are shown in white boxes. A global warming climate variant is displayed in dotted green for comparison. The light green areas indicate transitions from temperate to permafrost conditions or vice versa. The spikes are caused by the occurrence of short temperate climate periods (dark green). Illustration modified after Becker et al. (2014).

The above example of how to explore, firstly, climate scenario impacts on landscape evolution (Fig. 5), and then climate and landscape evolution impacts on effective dose calculations (Fig. 6), is a good illustration of how to conceptualise the "biosphere" for any site as preparation for dose modelling in a PCSA. Properties and processes will always be site specific, but to be able to support the dose model calculations with long-term site understanding and physically constrained information is a general need.

8. Accounting for uncertainties in modelling environmental change and building confidence in dose modelling

The preceding sections of this paper draw on international experience to describe how key processes that drive environmental change can be identified and assessed, leading to narratives of climate and landscape change that provide a basis for radiological assessments. This section discusses the management of uncertainties in modelling environmental change and in the subsequent modelling of radiological impacts, drawing on experience of the application of biosphere assessment approaches.

The management of uncertainty is a key component of long-term dose assessments. Radiological assessments of geological repositories are subject to unavoidable uncertainties concerning the description of environmental change, the representation of radionuclide release and transport, human habits, and potential exposures in the biosphere. The use of a traceable and systematic approach to support narratives of long-term climate and landscape change, based on the latest scientific understanding, helps to build confidence in the plausibility of resulting dose assessments. Such narratives can be used in support of further process-based modelling, including catchment-scale hydrological modelling and particle tracking, to explore issues such as well interception and groundwater discharge areas. The complexity of processes represented in these detailed models, together with their associated computational solution, mean that the modelling may only represent snapshots in time; uncertainties in these supporting models are typically addressed through alternative deterministic simulations. The use of such narratives and models in support of dose assessment modelling requires interpretation, which can include interpolation, extrapolation and simplification.

Uncertainties in long-term dose assessments can be managed by assessing a range of potential future evolution scenarios and by complementing complex models with simple and more transparent reference biosphere models. The latter can help to check the robustness of the complex models and can help in communicating the degree of confidence in assessment results to key stakeholders. The impact of conceptual model uncertainty can be addressed by alternative and/or independent formulations of the modelled system. These need not comprise full alternate site models, but can focus on key aspects of the system (e.g. Kirchner et al., 1999; Kłos et al., 2015; Walke et al., 2015; Xu et al., 2017). However, significant uncertainties will always remain.

9. Discussion and conclusions

The methodological approach that has been developed within the MODARIA project, together with the technical developments in long-term climate modelling made in support of that project, complemented by developments of representations of landscape development in ongoing national programmes, as described above, jointly facilitate the consideration of climate change and landscape development within PCSA that can be applied to a wide range of site and repository types, and at different stages of the development of a disposal option, ranging from generic, initial studies to detailed site-specific assessments. The methodology has been set out as a road map, as described in Lindborg et al. (2017). This provides a practical framework and common basis for future assessment work that is consistent with international recommendations and guidance, as well as the latest technical developments.

The level of ambition in detailed application should depend on the stage of development of the repository and be proportionate to the hazard associated with the waste in question, including the timeframe over which it is hazardous and the scope for environmental change in different locations.

Global climate results at a 200 km scale have been generated in the MODARIA project for a wide range of carbon dioxide emissions scenarios, ranging from no anthropogenic emissions to a prolonged business-as-usual scenario, using a newly developed emulator underpinned by an ensemble of AOGCM runs. These global results could be used in any safety assessment programme worldwide in which the focus was on radiological impacts during the current interglacial episode. Ongoing studies sponsored by SKB and Posiva have the potential to extend this applicability to multiple glacial-interglacial cycles. However, even in the context of applying the results to the current interglacial episode, it would be desirable to explore uncertainties in these results by comparing them with emulators conditioned on the results from alternative AOGCMs. Also, whereas results at a resolution of 200 km may be sufficient for many assessment purposes, there may be circumstances in which downscaling of these results will be appropriate. Since such downscaling depends strongly on the local geographical context, the project was not able to present results that are applicable anywhere world-wide. However, it has been demonstrated how physical-statistical downscaling, the preferred method, can be applied to AOGCM results for the UK. A similar approach could be applied to results from the emulator at any location of interest to provide long time series of downscaled climatic information.

Once climate evolution data are available at appropriate spatial and temporal resolution, they can be used to drive landscape-development models along with other relevant data, notably crustal uplift rates which are relevant both to shoreline regression and to river incision.

Again, landscape development is strongly dependent upon local geography, so the MODARIA project was limited to discussions of the relevant issues and presented as an approach that, in turn, is supported with illustrative examples for warm, arid and temperate conditions, periglacial conditions and glacial conditions as well as transitions between them. These illustrate the approach adopted to construction of narratives for environmental change, based on the assumptions used in climate modelling and downscaling. Different aspects of the narratives can be developed and used differently within a single assessment, but it is important that they draw on the same foundation.

The next part of the methodology concerns the use of these narratives in radiation dose assessments. The approach adopted draws on experience of the application of biosphere assessment approaches, such as those discussed in IAEA (2016), as well as on-going project specific assessments. It is highlighted that the narratives can be used in various ways to support the assumptions for dose assessment models. The choice of simplifying assumptions can be an important consideration, along with how to address uncertainties in the context of present-day conditions and the treatment of future climatic and landscape conditions.

The case studies that have been reviewed and evaluated demonstrate the value of a step-by-step approach in building confidence in dose modelling results, show the potential value of the use of analogues, and illustrate the role of stakeholder engagement in building trust. Description of the landscape at the present day and how it may evolve in the future is an aspect of the post-closure assessment process that is particularly accessible to, and understandable by, various stakeholder groups. Descriptions of future biosphere characteristics and human behaviour can appear speculative and subject to challenge. There is, therefore, a need to carefully distinguish those aspects of the assessment that are based on quantitative analyses (e.g. derived from climate and landscape models), from those that are based on regulatory requirements or other judgements and decisions. It is recognised that, in practice, the distinction is not clear cut and that some aspects will be determined by judgemental interpretations of quantitative modelling results. In this context, uncertainty analyses play an important role in investigating the alternative scenarios that arise from different points of view on assessment issues, and determining the robustness of safety arguments across these alternative points of view. Engagement with stakeholders is essential both to explain the basis of quantitative aspects of the assessment and to support development of consensus on those aspects where judgement has the predominant role. An important example is the selection of assumption(s) for anthropogenic CO_2 releases that depend upon a combination of technical, economic and political factors.

Noting these issues, it is highlighted that the results produced through the application of the methodology are only intended as projections of possible futures based on a set of assumptions, i.e. reference futures. Therefore, as highlighted in the context of climate and landscape narratives above, it is emphasised that assessments must not be considered as predictions of the future. Rather they should be considered as illustrative projections that encompass plausible future situations to an extent that is sufficient to provide confidence in the safety of a disposal facility. Notwithstanding the uncertainties that exist, it has been shown, through research reviewed and undertaken in the MODARIA project, that quantitative long-term climate modelling is sufficiently developed and robust to define an envelope of reference futures for use in safety assessments of radioactive waste repositories, as supported by understanding of paleoclimatic conditions. The climate models that can be used for this purpose have limited spatial resolution and in some cases downscaling is necessary. Physical statistical methods exist to do this, but local statistical data are needed to apply them. Qualitative downscaling can also be used.

Quantitative modelling of landscape evolution and the linkage with climate modelling has been significantly developed in recent years but not for all potentially relevant climates and landscapes. Further work in this area is needed and special attention may have to be given to more detailed understanding of the first few thousand years after disposal. This goes beyond the typical focus of the IPCC (see IPCC, 2013) but is especially relevant to near-surface disposals and the long-term management of radioactively contaminated legacy sites.

Although the focus of the studies undertaken in MODARIA was radiation dose assessment following releases to the biosphere, the methodology and results obtained should be valuable in a wider post-disposal safety assessment context, e.g. addressing the effects of climate change and landscape development upon releases to the biosphere [see BIOPROTA (2014) for a discussion of approaches to representing the interface between the geosphere and the biosphere]. They may also be of interest to those with an interest in assessment of the post-disposal impact of chemically hazardous materials in radioactive waste repositories, and in the general issue of the disposal of hazardous wastes.

Finally, it is noted that the IAEA has set up a second phase of MODARIA that includes review and enhancement of the BIOMASS Reference Biospheres Methodology (IAEA, 2003). This addresses the developments in understanding and representation of climate-driven environmental change discussed here, alongside many technical and other developments, and is being implemented in parallel with related work within the BIOPROTA forum. Initial work has been reported in BIOPROTA (2017).

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